

**FINAL REPORT-NAG5-3226:
“THE FUNDAMENTAL PHYSICAL
PROCESSES PRODUCING AND
CONTROLLING STELLAR
CORONAL/TRANSITION
REGION/CHROMOSPHERIC
ACTIVITY AND STRUCTURE”**

Our previous LTSA grant (1995–2000: T.R. Ayres, PI; A. Brown, Co-I) supported a long-term collaborative investigation of stellar activity and atmospheric structure. LTSA provided a vital funding base that has enabled us to tackle projects of larger scope than could have been supported by typical Guest Observer grants alone, and to participate in related collaborative studies with other investigators (e.g., *IUE* work on AGN, chromospheres of A dwarfs, CO in R CrB stars, etc.) where otherwise we would have lacked direct funding.

Our LTSA research has utilized current NASA and ESA spacecraft, supporting ground-based IR, radio, and sub-mm telescopes, and the extensive archives of *HST*, *IUE*, *ROSAT*, *EUVE*, and other missions. Our research effort has included observational work (with a nonnegligible groundbased component), specialized processing techniques for imaging and spectral data, and semiempirical modelling, ranging from optically thin emission measure studies to simulations of optically thick resonance lines.

We are the leaders of a significant cool star research group at CASA; consisting of ourselves, three postdoctoral researchers (Drs. Phil Bennett, Graham Harper, Guy Stringfellow) and one graduate student (Rachel Osten). We have close ties with local cool star colleagues at JILA and the High Altitude Observatory. As a measure of our standing in the community, we were selected to host the 12th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun—the major biennial international meeting in our field—

which was held in Boulder, in early August 2001.

In our previous LTSA efforts, we have had a number of major successes, including most recently: organizing and carrying out an extensive cool star UV survey in *HST* cycle 8; obtaining observing time with new instruments, such as *Chandra* and *XMM* in their first cycles; collaborating with the *Chandra* GTO program and participating with the *Chandra* Emission Line Project on multi-wavelength observations of HR 1099 and Capella.

The main broad-brush themes of our previous investigation:

(a) Where do Coronae Occur in the Hertzsprung–Russell Diagram?

We have made significant progress understanding the coronal life cycles of rapidly evolving giant and supergiant stars as they cross into the cool-half of the H–R diagram from the upper main sequence. *HST* UV spectra of key objects led us to the “magnetospheric” scenario (coronae dominated by a fossil magnetic field, rather than one resulting from a regenerative “dynamo,” as in the Sun), which is testable using the new generation of X-ray spectroscopic observatories. We have explored the onset of activity in late-A stars (in collaboration with T. Simon). In the case of enigmatic 71 Tauri (F0 V), second brightest X-ray source in the Hyades, we discovered a close-in late-type companion (in a STIS long-slit spectrum) which appears to be responsible for the anomalous coronal emission. Among the cooler K and M giants we have inventoried the amount of coronal plasma both via direct X-ray observations and by using 10^5 K UV spectral proxies. Evidence suggests that magnetic activity does not, as previously thought, die out during the later stages of evolution, but instead its overt signature— 10^6 K coronal X-ray emission—is likely to be

hidden beneath large amounts of overlying cooler gas ("smothered coronae"). [Papers 5, 6, 8, 9, 12, 14, 15, 16, 17, 18, 19, 20; see "References" section for list]

(b) Winds of Coronal and Noncoronal Stars

Detailed comparative studies of UV emission line profiles were used to characterize the properties of winds in evolved giants, including those (such as α TrA [K2 II]) at the critical juncture in the H-R diagram where the so-called "hybrid" stars display mixed signatures of coronal gas and cool winds. UV studies were supported by extensive centimetric observations carried out at radio telescopes around the world. Another approach to understanding the wind acceleration close to the stellar surface was line-of-sight sampling in eclipsing binaries using hot secondaries as background light sources. [2, 9, 12, 14, 15, 27, 31, 33]

(c) Activity, Age, Rotation Relations

The relationship between stellar activity and controlling parameters such as rotation and age were investigated in widely differing situations including pre-main sequence stars, solar-type dwarfs in young galactic clusters, and hyperactive tidally-synchronized binaries. Strong evidence was found for large-scale magnetic fields within the outflow from the pre-MS star T Tau S. The activity levels of young MS stars were examined in the Hyades, Pleiades, and α Persei clusters, and the Pleiades Moving Group (the "Local Association"). The cluster work was used to estimate the levels of the Sun's ionizing flux in the primitive solar system, a key factor in the radiative erosion of the early Martian atmosphere, and relevant to astrobiology issues. Our EUV studies of RS CVn binaries provide the most extensive sampling of active binary coronal flare rates, energies, and behavior to date. [1, 3, 4, 6, 7, 11, 14, 16, 18, 23, 24, 26]

(d) Atmospheric Inhomogeneities

One of our main concerns has been the quantitative characterization of inhomogeneities within stellar outer atmospheres. We have uncovered many cases where plasmas with greatly differing physical conditions apparently exist in close proximity (for example, the pumping of cold CO molecules in the atmospheres of red giants by warm chromospheric O I photons having relatively short diffusion lengths). Our efforts are most developed in the case of the Sun, where we have utilized *SOHO* UV spectroscopy, *TRACE* chromospheric imaging, and groundbased mapping in the 5 μ m CO bands to dissect thermal and dynamical structures of the crucial "magnetic transition zone." We are undertaking an extensive survey of the stellar CO bands (with the NOAO PHOENIX spectrometer), to complement the hot gas diagnostics from our UV and X-ray programs. [2, 5, 12, 15, 19, 25]

(e) Heating Mechanisms, Subcoronal Flows, & Flares

The physical processes heating and controlling stellar chromospheres and coronae imprint a variety of signatures on the emission line profiles formed in these regions. Spectroscopy (in the UV, and now in the soft X-ray) is the key tool to probe profile asymmetries (due to winds, and other types of directed flows), and multiple emission components in the lineshapes, formed in regions with widely differing dynamical environments (from relatively quiescent gas to violent "explosive events"; e.g., the HR 1099 flare from the joint *Chandra-HST-EUVE-VLA* campaign in September 1999). Coronal light curves from the extensive *EUVE* collection are shedding new light on the mechanics of giant flares on active single stars and binaries. [1, 3, 8, 11, 13, 21, 30, 32]

(f) Development of Analysis and Modelling Tools

Last, but not least, we have continued our development of sophisticated software for the analysis of *HST*, *EUVE*, *ASCA*, *ROSAT*, *IUE* and now *Chandra* and *FUSE* spectral data; including specialized spectral extraction tools for the *Chandra* High Energy Transmission Grating Spectrometer (HETGS), used in the 1999 HR 1099 campaign. Software for temporal analysis of *EUVE* and *IUE* data were used extensively to measure the coronal variability of active binaries and the UV variability of AGNs. Specialized display and measuring algorithms were created for our GHRS and STIS projects. New modelling tools were developed for radiative transfer simulations ranging from multi-dimensional simulations of the inhomogeneous solar chromosphere to the complex wind of the M supergiant α Ori. [1, 2, 5, 9, 18, 23, 25, 26, 27]

The following section lists refereed journal articles that resulted from research carried out under the LTSA grant. In addition, numerous papers were published in conference proceedings or as abstracts, for example, in American Astronomical Society meetings.

Publications

1. Clayton, G.C., & AYRES, T.R. 2001, "Long-Slit Observations of Extended C II λ 1335 Emission Around V854 Centauri and RY Sagittarii," ApJ, 560, 986.
2. BROWN, A., Bennett, P.D., Baade, R., Kirsch, T., Reimers, D., Hatzes, A.P., & Kürster, M. 2001, "Ultraviolet Eclipse Observations and Fundamental Parameters of the Binary HR 2554 (G6 II + A1 V)," AJ, 122, 392.
3. Harper, G.M., BROWN, A., & Lim, J. 2001, "A Spatially-Resolved, Semi-Empirical Model for the Extended Atmosphere of α Orionis (M2 Iab)," ApJ, 551, 1073.
4. Harper, G.M., Wilkinson, E., BROWN, A., Jordan, C., & Linsky, J.L. 2001, "Identification of Fe II Emission Lines in *FUSE* Stellar Spectra," ApJ, 551, 486.
5. AYRES, T.R., BROWN, A., Osten, R.A., Huenemoerder, D.P., Drake, J.J., Brickhouse, N., & Linsky, J.L. 2001, "*Chandra*, *EUVE*, *Hubble*, and VLA Multi-Wavelength Campaign on HR1099: Instrumental Capabilities, Data Reduction, and Initial Results," ApJ, 549, 554.
6. Osten, R.A., BROWN, A., AYRES, T.R., Linsky, J.L., Drake, S.A., Gagne, M., & Stern, R.A. 2000, "Radio, X-ray, and EUV Coronal Variability of the Short-Period RS CVn Binary σ^2 Corinae Borealis," ApJ, 544, 953.
7. Wood, B.E., Ambruster, C.W., BROWN, A., & Linsky, J.L. 2000, "The Mg II and Ly α Lines of Nearby K Dwarfs: ISM Components and Flux Measurements," ApJ, 542, 411.
8. AYRES, T.R. 2000, "The SOHO-Stellar Connection," Solar Phys., 193, 273.
9. Simon, T. & AYRES, T.R. 2000, "71 Tauri: Hyades Enigma Resolved?" ApJ, 539, 325.
10. AYRES, T.R., Osten, R.A., & BROWN, A. 1999, "The Rise and Fall of μ Velorum: A Remarkable Flare on a Yellow Giant Star Observed with the Extreme Ultraviolet Explorer," ApJ, 526, 445.
11. AYRES, T.R. 1999, "Digging Deeper in the Coronal Graveyard: Postscript," 1999, ApJ, 525, 1009

12. AYRES, T.R. 1999, "Sleuthing the Dynamo. II. *HST* Goddard High Resolution Spectrograph Observations of Solar-Type Dwarfs in Young Galactic Clusters," *ApJ*, 525, 240.
13. Clayton, G.C., AYRES, T.R., Lawson, W.A., Drilling, J.S., Voitke, P., & Asplund, M. 1999, "First Observations of an R Coronae Borealis Star with the Space Telescope Imaging Spectrograph: RY Sagittarii near Maximum Light," 1999, *ApJ*, 515, 351
14. Osten, R.A. & BROWN, A. 1999, "EUVE Photometry of RS CVn Systems: Four Flaring Megaseconds," *ApJ*, 515, 746.
15. Carpenter, K.G., Robinson, R.D., Harper, G., Bennett, P., BROWN, A., & Mullan, D.J. 1999, "GHRS Observations of Cool, Low-Gravity Stars. V. The Outer Atmosphere and Wind of the Nearby K-Supergiant λ Velorum," *ApJ*, 521, 382.
16. Güdel, M., Linsky, J.L., BROWN, A., & Nagase, F. 1999, "Flaring and Quiescent Coronae of UX Arietis: Results from *ASCA* and *EUVE* Campaigns," *ApJ*, 511, 405.
17. Brunner, A.R., Clayton, G.C., & AYRES, T.R. 1998, "A Search for an Emission-Line Region in the Hydrogen-deficient Carbon Star HD 182040," *PASP*, 110, 1412.
18. Robinson, R., Carpenter, K.G., & BROWN, A. 1998, "Goddard High-Resolution Spectrograph Observations of Cool Low-Gravity Stars. IV. A Comparison of the K5 III Stars α Tauri and γ Draconis," *ApJ*, 503, 396.
19. Simon, T., & AYRES, T.R. 1998, "High-Excitation Emission Lines in the Far-Ultraviolet Spectrum of the Late-A Star α Cephei," *ApJ*, 500, L37.
20. AYRES, T.R., Simon, T., Stern, R.A., Drake, S.A., Wood, B.E., & BROWN, A. 1998, "The Coronae of Moderate-Mass Giants in the Hertzsprung Gap and the Clump," *ApJ*, 496, 428.
21. Linsky, J.L., Wood, B.E., BROWN, A., & Osten, R.A. 1998, "Dissecting Capella's Corona: GHRS Spectra of the Fe XXI λ 1354 and He II λ 1640 Lines from each of the Capella Stars," *ApJ*, 492, 767.
22. AYRES, T.R., BROWN, A., Harper, G.M., Bennett, P.D., Linsky, J.L., Carpenter, K.G., & Robinson, R.D. 1997, "Digging Deeper in the Coronal Graveyard," *ApJ*, 491, 876.
23. Wanders, I., Peterson, B.M., Alloin, D., AYRES, T.R., & 53 additional co-authors, 1997, "Steps toward Determination of the Size and Structure of the Broad-Line Region in Active Galactic Nuclei. XI. Intensive Monitoring of the Ultraviolet Spectrum of NGC 7469," *ApJS*, 113, 69.
24. Wood, B.E., Linsky, J.L., & AYRES, T.R. 1997, "Evaluating Possible Heating Mechanisms Using the Transition Region Line Profiles of Late-Type Stars," *ApJ*, 478, 745.
25. Piskunov, N., Wood, B.E., Linsky, J.L., Dempsey, R.C., & AYRES, T.R. 1997, "Local Interstellar Medium Properties and Deuterium Abundances for the Lines of Sight toward HR 1099, 31 Comae, β Ceti, and β Cassiopeiae," *ApJ*, 474, 315.

26. AYRES, T.R. 1997, "Evolution of the Solar Ionizing Flux," *JGR (Planets)*, 102, 1641.
27. Ray, T.P., Muxlow, T.W.B., Axon, D.J., BROWN, A., Corcoran, D., Dyson, J., & Mundt, R. 1997, "Large-scale Magnetic Fields in the Outflow from the Young Stellar Object T Tauri S," *Nature*, 385, 415.
28. AYRES, T.R., Simon, T., Stauffer, J.R., Stern, R.A., Pye, J.P., & BROWN, A. 1996, "Sleuthing the Dynamo: Hubble Space Telescope Faint Object Spectrograph Observations of Solar-Type Dwarfs in Young Galactic Clusters," *ApJ*, 473, 279.
29. Bennett, P.D., Harper, G.M., BROWN, A., & Hummel, C.A. 1996, "The Masses and Radii of the Eclipsing Binary Zeta Aurigae," *ApJ*, 471, 454.
30. Dempsey, R.C., Neff, J.E., Thorpe, M.J., Linsky, J.L., BROWN, A., Cutispoto, G., & Rodono, M. 1996, "Goddard High Resolution Spectrograph Observations of Variability in the RS CVn System V711 Tau (HR1099)," *ApJ*, 470, 1172.
31. Edelson, R.A., 19 authors, AYRES, T.R., et al. 1996, "Multiwavelength Observations of Short-Timescale Variability in NGC 4151. IV. Analysis of Multiwavelength Continuum Variability," *ApJ*, 470, 364.
32. Crenshaw, D.M., Rodriguez-Pascual, P.M., Penton, S.V., Edelson, R.A., Alloin, D., AYRES, T.R., et al. 1996, "Multiwavelength Observations of Short-Timescale Variability in NGC 4151. I. Ultraviolet Observations," *ApJ*, 470, 322.
33. BROWN, A., Deeney, B.D., AYRES, T.R., Veale, A., & Bennett, P.D. 1996, "Mg II Emission from Hybrid-Chromosphere Stars: 1.5 Decades of Chromospheric Variability Monitoring," *ApJS*, 107, 263.
34. Jones, K.L., BROWN, A., Stewart, R.T., & Slee, O.B. 1996, "Evidence for Narrow Bandwidth Highly Polarized Radio Emission from the RS CVn Binary HR 1099," *MNRAS*, 283, 1331.
35. Baade, R., Kirsch, T., Reimers, D., Toussaint, F., Bennett, P.D., BROWN, A., & Harper, G.M. 1996, "The Wind Outflow of ζ Aur: A Model Revision using *HST* spectra," *ApJ*, 466, 979.
36. AYRES, T.R., & Rabin, D. 1996, "Observations of Solar Carbon Monoxide with an Imaging Infrared Spectrograph. I. Thermal Bifurcation Revisited," *ApJ*, 460, 1042.

AUG 13 2002

OCG